I. Introduction

1. Definition of Thermofluids

The study of thermofluids integrates various disciplines of the field of thermal sciences. This field consists of such topics as thermodynamics, fluid mechanics, and heat transfer, all of which are discussed in various chapters of this book. The fascinating concept of *energy* is the common denominator in all these topics. Although we are intuitively familiar with energy through our various experiences it is, nonetheless, difficult to formulate an exact definition. One might say energy is the ability to do *work*, but then we must first define work. According to Huang we may hypothesize that "energy is something that all matter has." We leave the definitions and discussion of energy, *heat*, work, and *power* to the chapter on thermodynamics. In this chapter we introduce thermofluids and discuss the engineering applications of thermofluids in the design and operation of thermal systems, such as those used in power production.

Thermal systems deal with the storage, conversion, and transportation of energy in its many forms. These may include a jet engine that converts fuel energy to mechanical energy, an electric heater that converts electrical energy to heat energy, or even a shotgun, which converts chemical energy to kinetic energy. Having defined thermal systems, we now define fluids. In general, any substance that is not a solid can be considered as a fluid. In this book the only fluids, we consider in the design and operation of thermal systems are *liquids* and *gases* especially water and air, as they are by far the most abundant fluids on earth. Liquids and gases in thermal systems are referred to as *working fluids*. As discussed in the chapter on fluid mechanics, there are also other types of fluids such as blood, glue, lava, slurry, tar, and toothpaste, which are analyzed differently than liquids and gases.

From this brief introduction, we conclude that: *thermofluids is a subject that analyzes systems and processes involved in energy, various forms of energy, and transfer of energy in fluids*. Since fluids generally come in contact with solids, in this book we will include the study of energy transfer in both fluids and solids.

This book is prepared in seven chapters. In the present chapter, we discuss the three sources of energy for power production and describe various power producing systems. This provides sufficient background to start Chapter II and learn about thermodynamics and its associated laws governing the processes involved in thermal systems. This is followed by Chapter III on fluid mechanics and its related topics on the application of the working fluids in thermal systems. Chapter III deals exclusively with the flow of *single-phase* fluids. The topic of heat transfer in both solids and single-phase fluids is discussed in Chapter IV. Chapter V then

discusses the mechanisms associated with *two-phase flow*. Chapter V also discusses heat transfer when a fluid changes phase such as the boiling of water and condensation of steam. The knowledge gained in the first five chapters is then used in Chapter VI to discuss the applications of thermofluids in the design and operation of such thermal systems as heat exchangers (steam generators, feedwater heaters, and condensers), turbines, and pumps. Engineering mathematics covering a wide range of topics in advanced calculus is compiled in Chapter VII. This allows us in each chapter to focus exclusively on the topic at hand and prevents us from any need to discuss mathematics in these chapters.

2. Energy Source and Conversion

Energy is essential for most advances in society and the continuous improvement of the quality of life. We use a variety of means to convert energy for industrial, transportation, residential, and commercial applications.

From time to time, the world has experienced energy crises, defined as the shortage of supply of energy or the environmental consequences associated with the use of a source of energy. Such crises prove to be important reminders of how vital energy is for transportation, commerce, industry, and residential use. These crises also serve as the motivation to improve and broaden the application of energy sources and for the quests to find new sources of energy.

Figure I.2.1 shows the interaction between various forms of energy and the respective means of energy conversion. Let's examine this figure by first considering for instance, pumping water to a reservoir. The mechanical energy of the pump is used to lift water, hence increasing water's potential energy, and to fill the reservoir. The reservoir then returns the stored energy in water in the form of kinetic energy when we open the faucet in our homes. The pump itself must be powered by a prime mover such as an electric motor or an internal combustion engine, indicating conversion of electrical or chemical energies to mechanical energy.

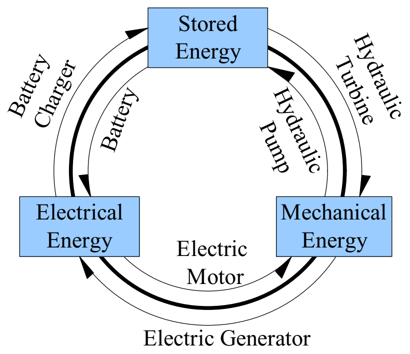

Figure I.2.1. Means of energy conversion (Marquand)

If water instead of flowing in the faucet is used to power a hydraulic turbine, the water kinetic energy would be converted back to mechanical energy. The mechanical energy in a generator is converted to electrical energy. The electrical energy may then be used to charge batteries, which then become the reservoir for stored energy. In this energy conversion process, one form of stored energy is converted to a new form of stored energy.

The converse is also possible when we use a battery to produce electrical energy, which can then be used in an electric motor to be converted to mechanical energy. The motor, in turn would serve as the prime mover of a hydraulic pump to fill a reservoir thus, converting the mechanical energy into stored energy.

Figure I.2.2 is a more comprehensive diagram of energy conversion including various types of energy and the conversion pathways between various types. For example, radiant, chemical, electrical, mechanical, and nuclear energies can be converted to thermal energy while thermal energy can be converted to mechanical and electrical energies.

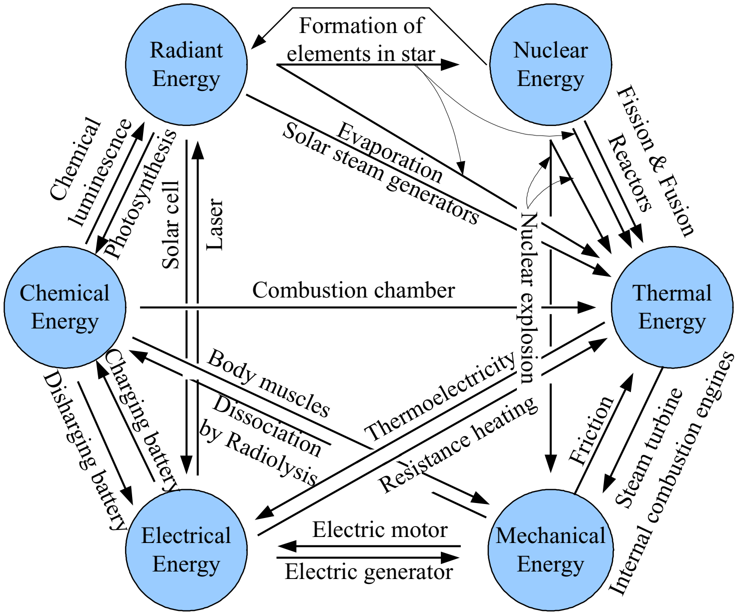

Figure I.2.2. Important forms of energy and the pathway for conversion (Marion)

The conversion of one type of energy to another takes place in what is known as a *process*. Many of such processes including the direction of a process and such concepts as efficiency are discussed in Chapter II. In the remainder of this chapter, we discuss various sources of energy and briefly describe various types of energy conversion system for power production.

3. Energy in Perspective

The world's energy resources must fulfill the needs of an increasing world population. The world energy resources are generally divided into three categories, fossil fuels, nuclear fuels, and green, renewable or alternative resources. Historically, wood was the primary source of energy before the industrial revolution. The first oil producing well was operational in 1859, which was followed by the introduction of the internal combustion engine (1876), the first steam-generated electric plant (Edison, New York city 1882), the steam turbine (1884), and the Diesel Engine (1892). We now discuss two important types of fuels; fossil and nuclear.

3.1. Fossil Fuels

This category consists of coal, oil, and natural gas. Today, over 80% of the world's energy supply is from fossil fuels, of which 60% is from oil and gas and the remaining 40% is from coal. Coal is pure carbon and natural gas is primarily methane hence, both of these fuels can be used without substantial processing. Petroleum, on the other hand, is found in the form of crude oil and must be refined for various applications. In the United States, coal is primarily used for power production and in industrial applications, while natural gas is used for industrial and residential applications as well as in power production. Petroleum in the United States is primarily used for transportation (54%) followed by industrial, residential, and power generation.

3.2. Nuclear Fuels

According to Einstein's equation $E = mc^2$, the energy obtained from 1 kg of uranium is equivalent to the burning of 3.4 thousand tons of coal[1]. Similarly from the conversion of mass to energy, we find that the energy equivalent of mass in a barrel of oil is over 2 billion times more than the energy obtained by its combustion. The share of power production from nuclear energy has increased since 1950. Nuclear energy is used primarily for power production, although nuclear reactors are also used to power naval surface ships and submarines. Battery powered submarines must surface periodically to recharge their batteries using diesel engines, which require an intake of oxygen to support combustion. Since no combustion occurs in a nuclear reactor to require oxygen, nuclear powered submarines can remain submerged indefinitely. The world's first nuclear-powered submarine was commissioned in 1954 and the first commercial nuclear power plant (90 MWe) became operational in Shippingport, Pennsylvania in 1957. The physical processes occurring in nuclear reactors can be classified as either *fission* or *fusion*.

[1] The energy equivalent of 1 gram of mass is $E = (1/1{,}000)$ kg $\times$ $(300{,}000{,}000)^2$ m^2/s = 9E13 J = 8.53E10 Btu.

Fission-Based Reactors

These reactors use heavy elements like uranium and plutonium as fuel. The atoms in these elements have a high possibility of splitting (fission) when exposed to neutrons. The energy obtained from such reactions is primarily due to the kinetic energy of the fission fragments. Fission reactors may be subdivided based on energy of the neutron used for fission. Reactors using low-energy neutrons and uranium are known as *thermal* reactors and reactors using high-energy neutrons and plutonium are referred to as *fast* reactors. Most of the world's nuclear reactors are thermal. As discussed in Chapter IVe, high-energy neutrons emerge subsequent to the fission of heavy elements. Striking the atoms of a moderator slows down or thermalizes fast neutrons.

Thermal reactors in the United States use water both as coolant and as moderator thus are referred to as *Light Water Reactors* (LWRs)[2]. Light water reactors can be divided into two major categories; *Pressurized Water Reactors* (PWRs) and *Boiling Water Reactors* (BWRs). Reactors that use gases like helium as coolant are known as *Gas Cooled Reactors* (GCR). Some fast reactors use a liquid metal, such as sodium, as coolant. These are referred to as *Liquid Metal Fast Breeder Reactors*, (LMFBR). The breeder reactors convert such *fertile* isotopes as ^{238}U and ^{232}Th to such *fissionable* isotopes as ^{239}Pu and ^{233}U, respectively. Thus, in such reactors, more fissionable nuclei are produced by conversion than are consumed by fission.

Fusion-Based Reactors

In a fusion process, two light nuclei such as deuterium and lithium fuse together in an intensely ionized electrically neutral gas known as *plasma*. The energy obtained in this reaction is in the form of the kinetic energy of the emergent nuclei. To compare the immense energy obtained from fusion in comparison with fission, we note that the energy produced by 1 kg of light nuclei in fusion is equivalent to the fission energy of about 256 kg of uranium. However, obtaining a sustained fusion reaction requires further research and development and has so far, remained elusive. To date, all fusion-based reactors are only experimental facilities.

4. Power Producing Systems

The power producing systems, used for transportation or for industrial and residential electric power consumption, can be divided into two categories. The first category includes most devices that directly convert other forms of energy into electricity, known as *direct energy conversion*. Such systems as photoelectric cells and thermoelectric generators produce electric power on smaller scale. The second category includes systems that their end result is turning the shaft of an

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[2] As discussed in Chapter VIe, thermal reactors may also use heavy water (deuterium instead of hydrogen) both as coolant and as moderator. These types of reactors are known as HPWR or CANDU (Canadian Deuterium Uranium).

electric generator to produce electricity based on Faraday's law of induction. Faraday's law is the basic principle for current central power stations generating electricity on a large scale.

Systems in the second category can be further divided based on whether a *thermodynamic cycle* is used for their operation. A thermodynamic cycle, as shown in Figure I.4.1 and discussed in Chapter II, consists of a heat source, a heat sink, an engine, and the working fluid. In a thermodynamic cycle, the working fluid is energized in the heat source and then directed to the engine to produce power. The working fluid is then passed through the heat sink and pumped back to the heat source to continue the cycle. Systems using a thermodynamic cycle may use coal, oil, gas, or nuclear heat in the heat source. A heat sink may consist of a radiator, a condenser, or a cooling tower. Power production from renewable resources such as solar energy and geothermal plants are also included in this group. Power producing systems that do not use a thermodynamic cycle include systems using such renewable energy resources as turbomachines (hydroelectric plants and wind turbines) and tidal power as discussed in Section 7. Fundamentals of turbomachines are discussed in Chapter VIc.

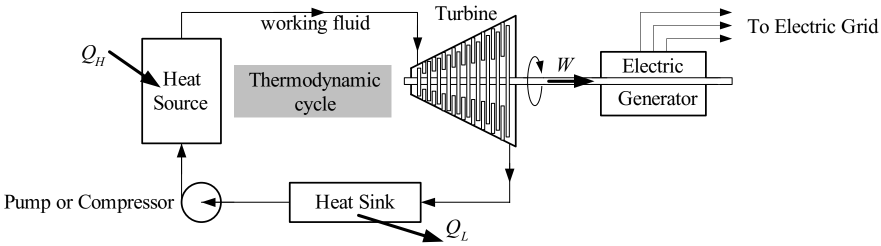


Figure I.4.1. A simplified diagram of a thermodynamic cycle for power production

5. Power Producing Systems, Fossil Power Plants

Power plants producing electricity on a large scale of hundreds to thousands of MWe, are concentrated in central power stations. Since power is extracted from the fossil fuels by combustion, systems using fossil fuels for power production are referred to as *combustion engines*. If such systems use coal or oil as fuel, they are known as *external combustion engines* in which there is no mixing of fuel with the working fluid. For example, in a coal power plant the energy obtained from the burning of coal is transferred to water flowing in the tubes through the tube wall. On the other hand, the *internal combustion engines* use refined oil, such as gasoline as well as natural gas. Thus, the working fluid in the internal combustion engines participates in the combustion process.

Internal combustion engines are used for power production in central power stations and in the automotive industry for transportation. Such engines can be divided into several categories; reciprocating piston-cylinder engines, rotary engines, and gas turbine engines as discussed next.

Reciprocating engines. The reciprocating piston-cylinder engine is a century old design that has stood the test of time and is used in an overwhelming majority of the world's automotives. As discussed in Chapter IIb, such engines generally use the *Otto* and the *Diesel* cycles. One cycle of a four-stroke cylinder-engine consists of six phases: *intake*, *compression*, *combustion*, *expansion*, *rejection*, and *exhaust*.

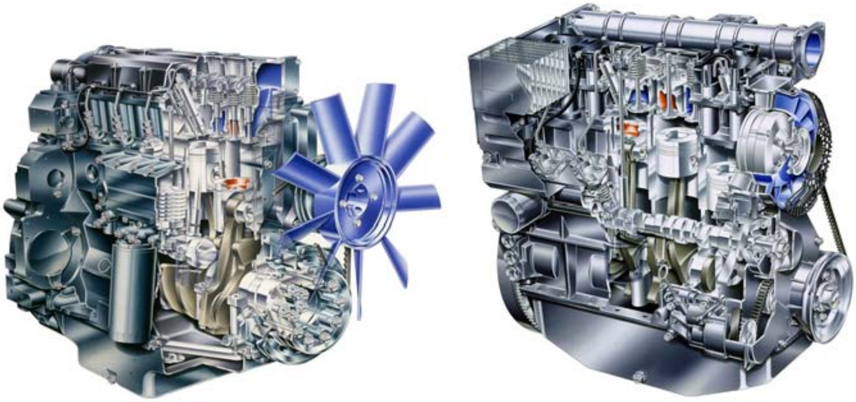


Figure I.5.1. Cutaway of an in-line six cylinder diesel engine (Courtesy Deutz AG)

The reciprocating motion of the engine piston, as transferred by the connecting rod to the crankshaft, causes the crankshaft to rotate. The crankshaft rotational motion is delivered to a gearbox to obtain the desired speed. The interface between the engine's flywheel and the gear box is provided by either a clutch or by a torque converter. These devices allow complete separation of engine and the gearbox and also provide synchronization at the time of engaging the engine with the gearbox. The output from the gearbox may be used in many ways, such as: an electric generator, a pump, the differential of a land vehicle for surface movement, the propeller of a cylinder-engine powered airplane, or the propeller of a ship for propulsion.

Reciprocating engines are equipped with camshafts to operate the intake and the exhaust valves. While the transfer of the crankshaft motion to the gearbox is through a clutch or a torque converter, the transfer of crankshaft motion to the camshaft to operate the engine's intake and exhaust valves is by gear, chain, or a belt called a timing belt. Opening of the intake and the exhaust valves is tied to the rotational motion of the crank through a rocker-arm mechanism. If the camshaft is placed below the top of the valves, the rocker-arm is operated by a push rod. If the camshaft is placed in the cylinder head then no push rod is required as the camshaft operates directly on the rocker arm. The intake and exhaust valves close by spring action.

Figure I.5.1 shows cutaways of a six-cylinder in-line diesel engine, which uses an injector and high compression ratio to reach the ignition temperature of the fuel mixture. In contrast, gasoline engines, whether using a carburetor, or a fuel injection system, use spark plugs to cause ignition for combustion. The piston is at-

tached to the connecting rod and is equipped with piston rings, which are essential components to ensure leak-tight compression. Some of the energy produced by the engine is used in an electric generator (dynamo) to charge the battery, circulate coolant around the engine jacket, or in some accessories such as car air-conditioning, and in operating the cylinder intake and exhaust valves through the camshaft.

Rotary engine. Unlike the cylinder-engine design in which pistons move in a reciprocal motion, another type of internal combustion engine uses a compartment and a rotor. The rotary combustion engine, or the Wankel engine after Felix Heinrich Wankel (1902–1988), was patented in 1936. However, problems associated with the seals at the rotor tips have prevented this type of engine from being used in a wider range of applications.

Various phases of a rotary engine cycle are shown in Figure I.5.2. As shown in Figure I.5.2-1, the rotor, rotating counterclockwise has blocked both inlet and exhaust ports, with the mixture being compressed while the combustion products are expanding. In Figure I.5.2-2, the fully expanded combustion products enter the exhaust pipe while fresh mixture enters the engine at the intake port. In Figure I.5.2-3, the fresh mixture enters the compartment, the fully compressed mixture is being ignited by the spark plug, and the combustion products leave the engine. In Figure I.5.2-4, the combustion has taken place and the mixture expands to deliver work to the rotor while the fresh mixture has filled the compartment and the inlet port is about to be blocked. The actual engine blocks of a rotary engine are shown is Figure I.5.3.

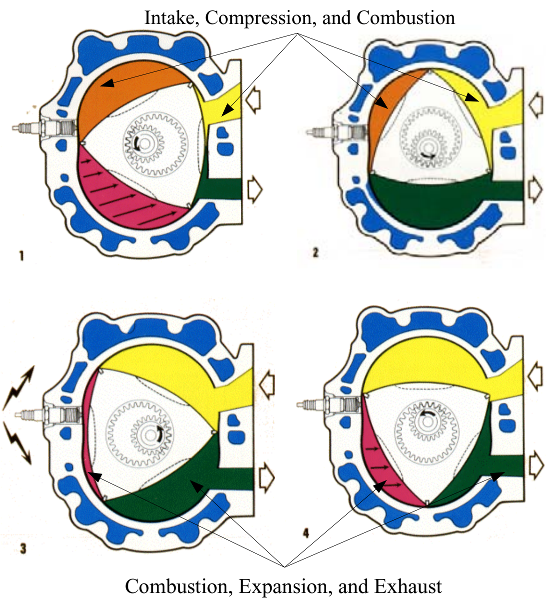


Figure I.5.2. Six phases of intake, compression, combustion, expansion, rejection, and exhaust in a rotary engine

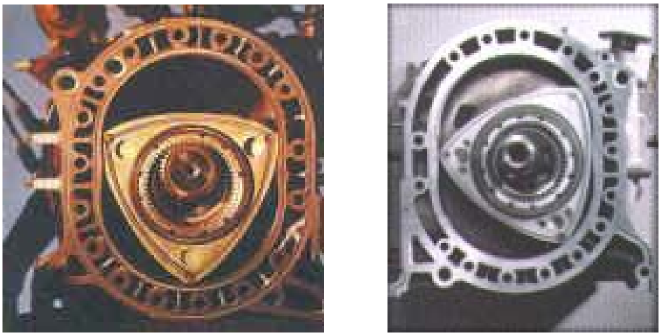


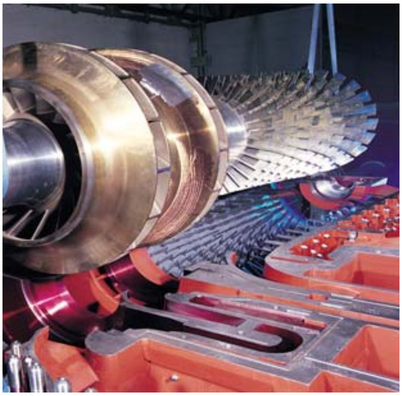
Figure I.5.3. Rotors, shaft, compartment, and the engine block of a rotary engine

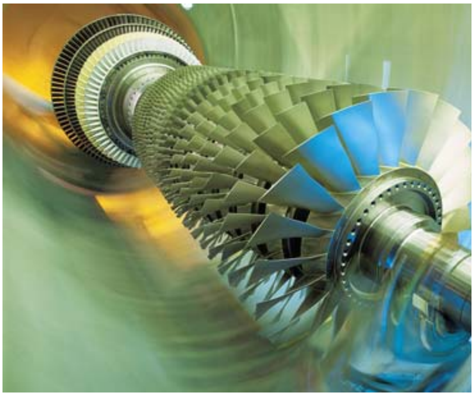
Reciprocating and rotary engines are generally water-cooled. However, some automotive engines and the pre-jet airplanes were air-cooled to reduce weight. Cylinders in the air-cooled engines of airplanes were oriented radially in a plane perpendicular to the air flow path to facilitate the flow of air through the engine. In the air-cooled engines, the rate of heat loss is enhanced by attachment of fins to the cylinder. Fins and fin efficiency are discussed in Chapter IVa.

Gas turbines are machines that convert the energy content of the working fluid to mechanical energy. Central power plants using gas turbines generally provide power at peak demand as compared with steam turbines that provide the base demand. Aviation gas turbines are referred to as jet engines. The advent of the jet engine was a turning point in aviation history as jet engines have much higher specific power, defined as power produced per engine weight, than reciprocal engines. The thrust produced by a jet engine follows Newton's third law: for every action there is an equal reaction in the opposite direction.

The principle of gas turbine operation, as discussed in Chapter IIb, is quite simple. Air entering the compressor is pressurized, to as much as 500 psia (3.4 MPa) and 1100 F (593 C) and is delivered to the combustion chamber where the mixture of air and fuel is ignited and reaches elevated temperatures (up to 3000 F, 1650 C). The energetic mixture then enters the turbine, transferring energy to the turbine rotor and leaving as exhaust gas. A portion of the turbine power is used to turn the compressor and to pump fresh air into the combustion chamber to continue the thermodynamic cycle. Figure I.5.4(a) shows the compressor and Figure I.5.4(b), a turbine rotor of a gas turbine power plant. Note that the compressor consists of combined axial (blades) and radial (disk) flow types mounted on the same shaft.

A jet engine consisting of compressor, combustion chamber, and turbine is known as a turbojet. Turbojets are well suited for crafts flying at high speeds and high altitudes. Other types of jet engines include *turbofan*, *turboprop*, and *turboshaft*. To increase the engine thrust, turbojets are equipped with a large fan, powered by the same turbine that powers the compressor and is referred to as a turbofan, as shown in Figure I.5.5. Turboprops on the other hand are turbojets that use a propeller instead of a fan. In turbofans and turboprops, about 85% of the compressed air bypasses the turbine to produce thrust, as discussed in Chapter VIc.





(a) (b)

Figure I.5.4. (a) A combined axial-radial flow compressor (b) a gas turbine rotor (Courtesy Siemens AG)

In turboshaft, the turbine power is delivered to a gearbox to drive a propeller or a helicopter rotor. This arrangement allows the rotor speed to be controlled independently of the turbine. In general, however, gas turbines used in a jet engine are well suited for relatively constant loads compared with the reciprocal engines that are well suited for load varying conditions. Engine endurance generally increases if operated under a constant load.

A cutaway of a turboshaft engine is shown in Figure I.5.6. In this engine, air is compressed by two radial compressors, which are driven by an axial turbine. In general however, jet engine compressors are primarily of axial type. Axial and radial designs of turbomachines are discussed in Chapter VIc.

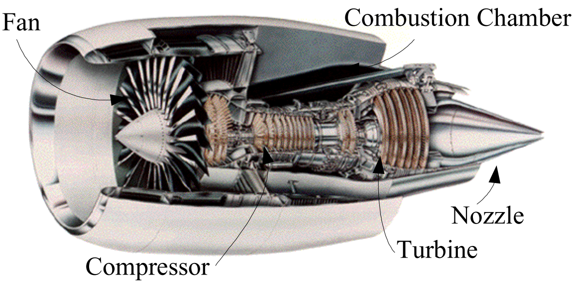


Figure I.5.5. Cutaway of a turbofan jet engine (Courtesy Pratt & Whitney)

To increase thrust, a second combustion chamber may be placed between the turbine and the nozzle. This chamber called the *afterburner*, increases the temperature of the gas before entering the nozzle hence, increasing thrust. As dis-

cussed in Chapter IIb, due to the high temperatures produced in the combustion chamber, gas turbines operate at higher thermal efficiency, defined as the ratio of power produced to the rate of energy consumed, compared with the efficiency of reciprocal engines or steam power plants.

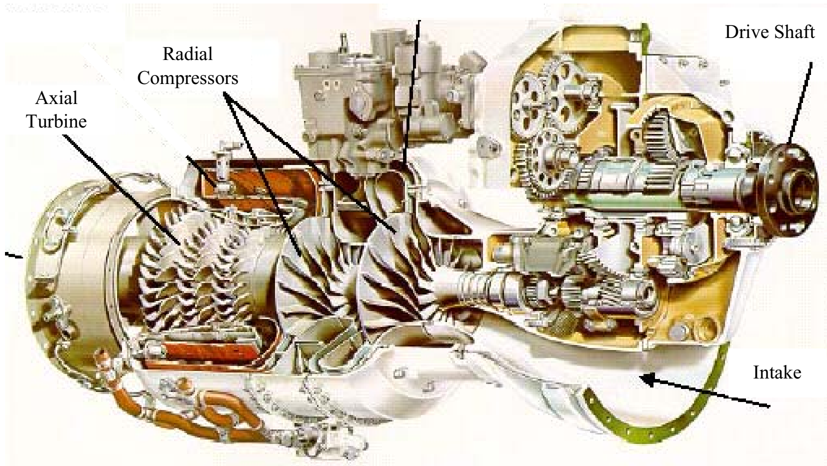


Figure I.5.6. A turboshaft engine using radial compressors and axial turbine

6. Power Producing Systems, Nuclear Power Plants

Nuclear power supplies about 17% of world's electricity. In France, about 80% of electricity is supplied by nuclear energy. In the United States, nuclear energy is the second largest source of electricity, providing power for 65 million homes. Unlike fossil fuels, nuclear energy does not produce any emissions to contribute to the greenhouse effect and global warming. Indeed if nuclear plants were to be replaced by fossil plants, the CO_2 emission worldwide would increase by 21% (Mayo). Schematics of two types of classic U.S. designed light water reactors are shown in Figure I.6.1.

Traditionally, nuclear reactors are classified based on neutron energy and the type of coolant/moderator. As mentioned in Section 3 and discussed in Chapter VIe, high-energy neutrons are referred to as fast and low energy neutrons are referred to as thermal neutrons. Reactors using high-energy neutrons for fission are referred to as fast reactors. Most commercial reactors are of the thermal type. Thermal reactors in addition to the coolant, as working fluid, also require moderator to thermalize neutrons. In most cases however, the coolant also plays the role of the moderator. There are generally three types of coolants used worldwide in power producing nuclear reactors: water, liquid metal, and gases such as helium. Water-cooled reactors are subdivided into light water (H_2O) and heavy water (D_2O) reactors, which use deuterium, an isotope of hydrogen.

All U.S. nuclear plants for power production are of the light water type being either a PWR or a BWR. In BWRs water boils inside the reactor vessel at a pressure of about 1050 psia (7.2 MPa), while in PWRs pressure is raised to about 2250 psia (15.5 MPa) to prevent water from boiling in the reactor. In PWRs, boiling takes place in the secondary side of the steam generator.

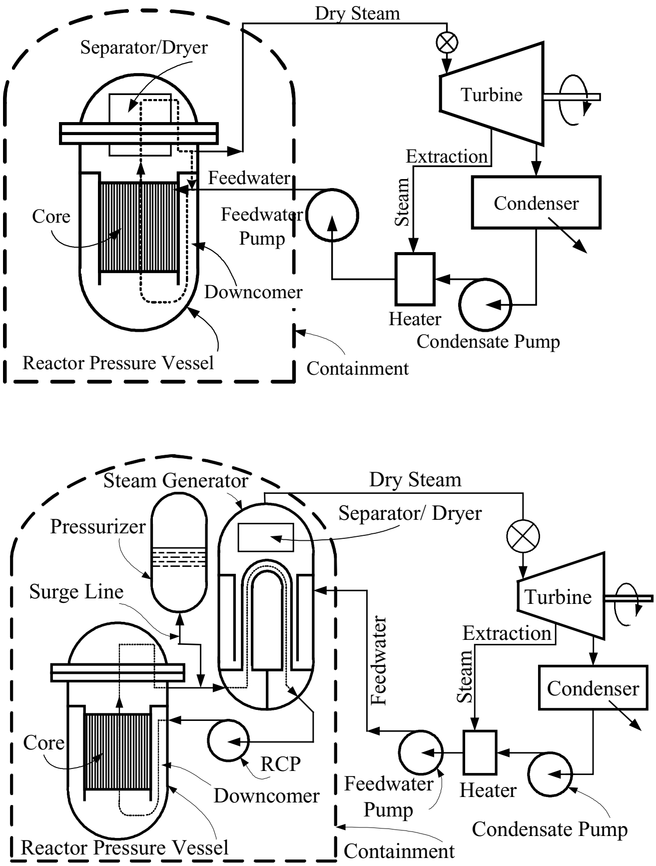


Figure I.6.1. Schematics of a BWR *(above)* and a PWR *(below)* plant

Gas cooled reactors (GCR) and advanced gas cooled reactors (AGR) use helium as the working fluid to reach high temperatures. GCRs are mostly used in England. For these types of reactors large compressors are required to circulate the coolant. Finally, a liquid metal fast breeder reactor (LMFBR) uses sodium as coolant.

6.1. Boiling Water Reactor

Since water boils in the *core* of a BWR, these types of reactors are known as direct-cycle power plants. The mixture of water and steam leaves the reactor core and enters the *separator-dryer* assembly to separate moisture from steam. As discussed in Chapter IIb, it is essential to deliver dry steam to the turbine. While dry steam enters the steam line and flows towards the turbine, the separated water at a temperature of about 550 F (288 C) flows downward towards the *downcomer* region of the reactor pressure vessel (RPV). The downcomer is an annulus between the RPV wall and the core barrel. The feedwater flow, delivered to the RPV by the main feedwater pumps also enters the downcomer but at about 375 F (190 C). These streams must mix well prior to entering the core. This task in the traditional BWR (designed by General Electric) is accomplished by two recirculation loops, each consisting of a recirculation pump, piping, and valves as shown in Figure I.6.2. The recirculation pumps withdraw water from the lower portion of the downcomer region and deliver to the inlet of up to 20 *jet pumps*. Jet pumps are made of stainless steel and consist of a suction inlet, throat (mixing section), and a diffuser. For plants operating at 1000 psia (7.2 MPa), the recirculation flow at a temperature of 545 F (285 C) then enters the *lower plenum* region of the RPV.

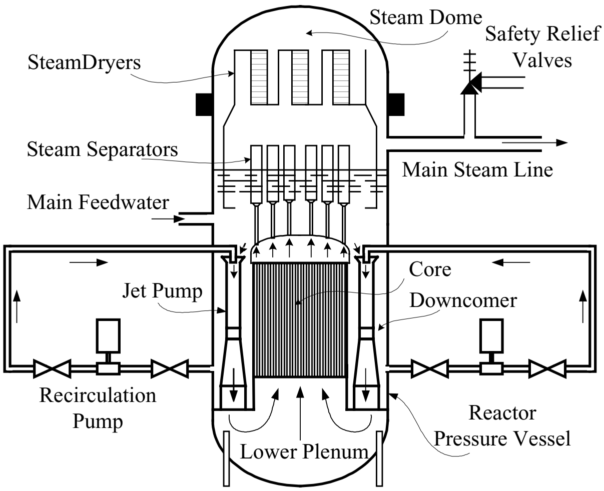


Figure I.6.2. A BWR reactor vessel

In the advanced BWR plants (ABWR, designed by Toshiba), the recirculation loops are eliminated. The recirculation in these plants takes place inside the RPV. Thus, the recirculation pumps and the jet pumps are combined and replaced by up to 10 *internal pumps* equipped with a motor (placed outside the RPV) and an impeller for forced mixing (placed in the downcomer). The recirculation pumps in BWRs and the reactor internal pumps in ABWRs play an important role in controlling the reactor power.

The well-mixed coolant entering the lower plenum flows upward into the core to remove heat from nuclear fission taking place in the fuel rods. The fuel rods are placed in square arrays of 8×8, 9×9, or 10×10 in a rectangular parallelepiped metal container referred to as fuel assembly or fuel bundle. The number of fuel bundles depends on the reactor power and may range from about 550 (for 800 MWe plants) to 870 (for 1350 MWe plants). Coolant, which at the core exit is a mixture of steam and water, leaves the fuel bundles and enters the upper plenum. From the upper plenum, coolant enters standpipes and is directed into the steam separator and steam dryer, as discussed earlier. The steam line leading to the turbine is equipped with safety and relief valves (SRV) as well as a main steam isolation valve (MSIV).

6.2. Pressurized Water Reactor

Unlike BWRs, no bulk boiling occurs in the core of a PWR; rather, boiling takes place in the secondary side of the steam generator (SG). Due to the presence of steam generators, PWRs are not direct-cycle power plants as they consist of a *primary side* and a *secondary side*. There is no mixing between the fluids flowing in each side, heat is transferred through the steam generator tube wall from the primary- to the secondary side. To prevent coolant from boiling in the primary side, pressure in a PWR vessel is more than twice that of a BWR (about 2250 psia, 15.5 MPa). Also, unlike BWRs, PWRs have an open core where flow can also move laterally between the fuel assemblies. There are generally over 200 fuel assemblies in the core of a PWR, each consisting of a square array of 15×15 fuel rods. The operating PWRs in the U.S. are of three designs: W (Westinghouse), CE (Combustion Engineering), and B&W (Babcock & Wilcox)[3]. The major differences are in the number and the type of the steam generators, as shown in Figure I.6.3.

The piping connecting the reactor vessel to the steam generator is referred to as *legs*. Pipes carrying water from the SG to the reactor vessel and from the reactor vessel to the SG are known as *Cold Leg* and *Hot Leg*, respectively. A pressure and inventory control tank, known as the *Pressurizer*, is connected to the hot leg through a *surge line*. The reactor coolant pumps (RCP) in the primary side of a PWR plant are located on the cold leg.

Shown in Figure I.6.4 is a two-loop PWR power plant. As seen in this figure, the outlet plenum of the steam generators is located on the suction of the reactor coolant pumps, delivering water through the cold leg to the downcomer region of the reactor vessel. Water then enters the lower plenum and flows to the core. Details of the reactor vessel are shown in Figure I.6.5(a). A small fraction of the coolant bypasses the core to cool the control rods. Water entering the core is at a temperature of about 550 F (288 C) and water leaving the core is about 600 F (316 C). The region on top of the core is referred to as the *core outlet plenum*. Water entering the outlet plenum from the core then flows towards the upper in-

[3] CE is now owned by BNFL (Westinghouse) and B&W by Framatome ANP.

ternals of the *upper guide structure* (UGS) and leaves the vessel through the hot leg to the inlet plenum of the steam generator. In the steam generator primary side, water from the inlet plenum moves upward toward the *tubesheet* and into the U-tubes. Hot water exchanges heat with the colder water in the secondary side, through the steam generator tube wall, and enters the outlet plenum of the steam generator to be pumped back to the reactor vessel.

Details of the secondary side of a U-tube steam generator are shown in Figure I.6.5(b). In the secondary side, the main feedwater pump delivers water to the downcomer at a relatively cold temperature of about 430 F (221 C). The colder feedwater is then mixed with the warmer water, which is at a temperature on the order of 530 F (277 C) and flowing downward from the separator-dryer assembly of the steam generator. The mixed stream flows downward toward the tubesheet and then upward when entering the tube bundle. The heat of the water transferred through the tube causes this mixed stream to boil. The two-phase mixture eventually leaves the top of the U-tubes and wet steam enters the separator assembly. Swirling vanes are installed in these assemblies to separate the entrained water droplets by centrifugal force. Steam then enters the dryer assembly to further reduce the moisture content. The dry steam then leaves the dryer assembly and enters the steam line to flow to the high-pressure stage of a steam turbine.

Similar to the BWR plants, the main steam lines in the PWR plants, connecting the steam generator to the turbine, are equipped with a series of valves including SRV, a steam dump valve, and a MSIV.

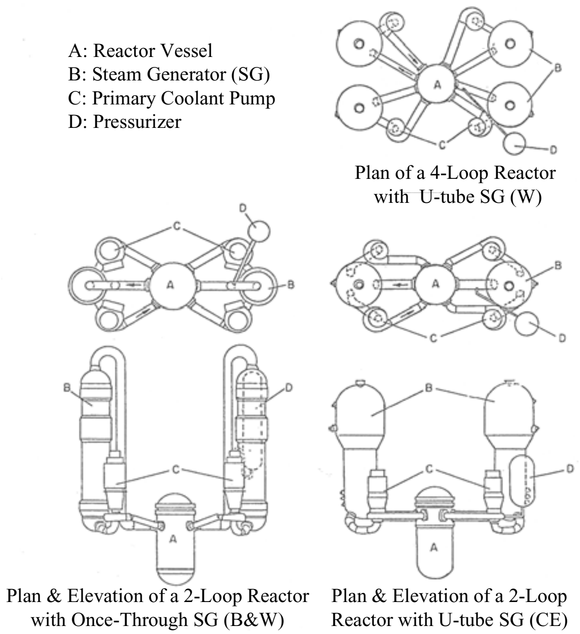


Figure I.6.3. Various classic U.S. designs of the operating PWRs (Todreas)

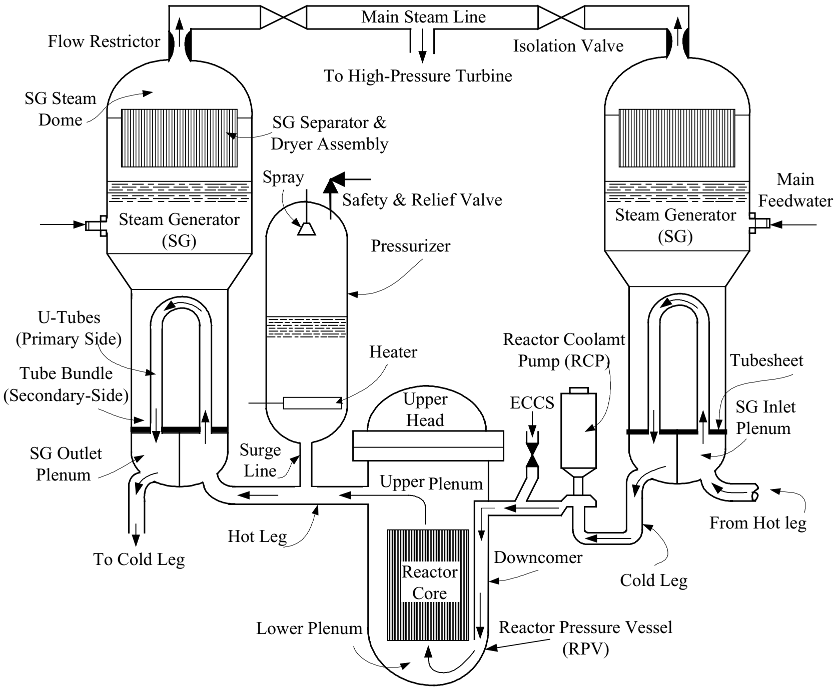


Figure I.6.4. Schematic of the RCS of a pressurized water reactor, using U-tube steam generators

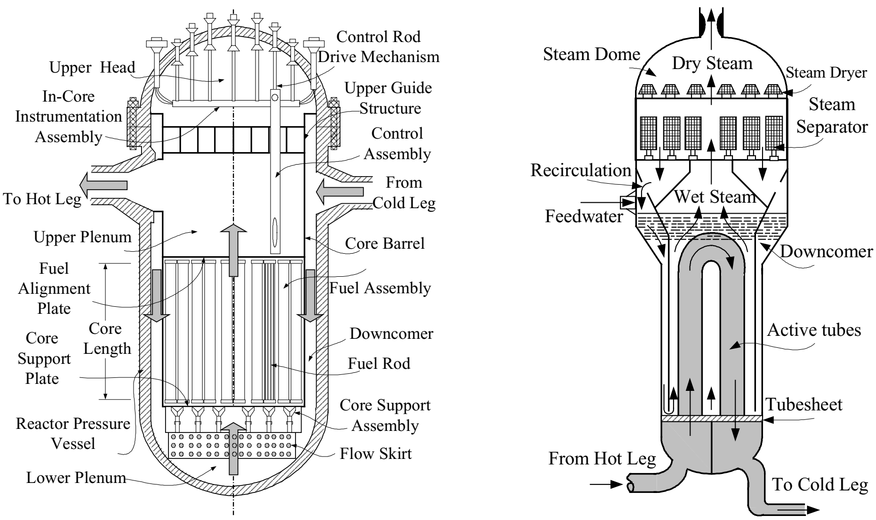


Figure I.6.5. Details of a PWR vessel **(a)** a PWR U-tube steam generator **(b)**

Fuel rods are thin hollow cylinders that are filled with uranium dioxide (UO_2) pellets. The hollow cylinder is referred to as cladding. The cladding material depends on the type of the nuclear reactor. In a LMFBR, the cladding is made of stainless steel while in LWRs, the cladding is generally made of an alloy of zirconium, known as *zircaloy*. The small *gap* between the fuel pellets and the inside of the cladding is filled with helium. During operation the fission gases that are released from the pellet also enter the gap region.

Steam turbines are the power producing machines of systems using a thermodynamic cycle. The shaft of a steam turbine turns the rotor of the electric generator. Steam turbines are also used as *prime movers* to power pumps. The stationary blades in the casing of steam turbine act as diffuser in directing the incoming steam to the blades of the rotor. As hot, energetic steam transfers its energy to the rotor, the diameter of the rotor increases to maintain the rate of momentum transfer. Figure I.6.6 shows the combined medium and low-pressure rotor and the double-flow low pressure rotor of a steam turbine

Figure I.6.6. Steam turbine rotor (courtesy Siemens AG)

7. Power Producing Systems, Greenpower Plants

The so-called greenpower or renewable energy sources consist of a wide range of sources including hydro, solar, geothermal, wind, and tidal. These sources of energy are briefly discussed next.

7.1. Hydropower Plants

After wood, falling water is the oldest source of energy. Romans used water wheels, to harness power. The first U.S. hydropower plant, built on the Fox River near Appleton, Wisconsin, generated electricity in 1882.

Figure I.7.1 shows the schematic of a hydropower plant including the turbine generator. The lake water, referred to as the head water, flows through a conduit known as the penstock towards the turbine. After turning the turbine runner, water flows in the draft tube to become the tail water to flow in the river, downstream of the turbine. As described in Chapter VIc, the turbine runner may be of *Kaplan*,

Francis, or *Pelton* type, which then turns the shaft of the electric generator. Shown in Table I.7.1 are the top 16 hydroelectric plants with respect to power production. By the late 20th century, hydroelectric produced about 25% of the global electricity and 5% of the total world energy, about 2,044 billion kilowatt-hours. The disadvantage of hydropower plants includes a large initial investment and a need for large bodies of water, with adverse effect on the river's ecological system and susceptibility to unfavorable weather conditions such as drought. Hydropower plants can be classified in terms of water flow rate and the difference between the elevations of water surface and the turbine. As discussed in Chapter III, this height is referred to as *Head*.

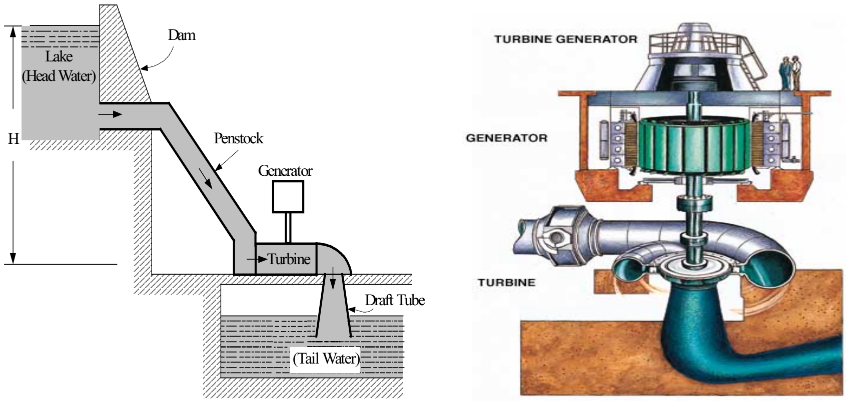


Figure I.7.1. Schematic of a hydropower plant to convert potential energy to electric power

Table I.7.1. Power output (MWe) of the world's largest hydropower plants

Name of Dam	Location	Present	Ultimate	Year operational
Itaipu	Brazil/Paraguay	12,600	14,000	1983
Guri	Venezuela	10,000	10,000	1941
Grand Coulee	U.S.A.	6,494	6,494	1967
Sayano-Shushensk	Russia	6,400	6,400	1989
Krasnoyarsk	Russia	6,000	6,096	1968
Churchill Falls	Canada	5,428	5,428	1971
La Grande 2	Canada	5,328	5,328	1979
Bratsk	Russia	4,500	4,600	1961
Moxoto	Brazil	4,328	4,328	1974
Ust-Ilim	Russia	4,320	4,320	1977
Volga	Russia	2,543	2,560	1958
Niagara	U.S.A.	2,190	2,400	1961
Volga	Russia	2,100	2,300	1955
Aswan	Egypt	1,750	2,100	1967
Chief Joseph	U.S.A.	1,024	1,950	1961
St. Lawrence	Canada – U.S.A.	1,880	1,880	1958

The Three Gorges Dam in China, 60 stories high and 2.3 kilometer long, will be the world largest dam. Upon completion in 2009, its 26 turbines will generate 18,200 MW electricity.

Low head and high flow rate are characteristics of rivers. For such condition, water is directed towards the turbine rotors known as the axial-flow turbines or *Kaplan rotor*. In this type, water flows between the vanes of the propeller and imparts its momentum to the rotor, which in turn is connected to the electric generator shaft. Figure I.7.2 shows an axial flow rotor.

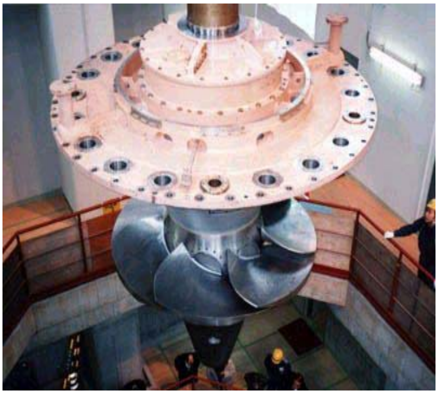


Figure I.7.2. Rotors of axial flow, Kaplan turbine (courtesy Toshiba Corporation)

High head and low flow are characteristics of water reservoirs on a mountaintop. The turbine used to harness the water power in such cases is generally of the impulse type using the *Pelton wheel* named after Lester Allen Pelton, who patented his wheel in 1889. As shown in Figure I.7.3, the Pelton wheel consists of buckets attached to the perimeter of a rotating wheel. Depending on the site, the wheel may be attached to a horizontal shaft or may be rotating horizontally connected to a vertical shaft. In this type of turbine, water is directed into injectors so that a jet of water strikes the bucket at high speed to turn the wheel. There may be one or as many as six injectors directing water towards the buckets of the wheel. The speed of the jet of water may reach values as high as 560 ft/s (171 m/s). A needle valve throttles the flow in the injectors. The wheel is placed in a casing for safety and to prevent water splashing. The principles of impulse turbines using the Pelton wheel are discussed in Chapter VIc.

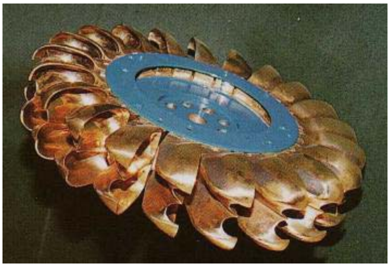


Figure I.7.3. Pelton wheels of impulse turbines

Medium head, turbines are also of reaction type. Such turbines use the Francis runner, as shown in Figure I.7.4. Water enters from the side, flows between the vanes of the runner, and exits through the center.

Figure I.7.4. Runners of radial flow turbines, Francis turbine (courtesy Toshiba Corporation.)

7.2. Solar Power Plants

Solar energy, in the form of electromagnetic radiation that reaches the earth, by far surpasses all other sources of energy in magnitude. However, large scale power production by direct conversion of solar radiation to electricity by photovoltaic is still in the research and development stage. Solar collectors are now used as a residential heat source and for commercial applications such as space heating, and to a lesser extent for the generation of electricity. Large-scale power production by the use of solar collectors presently requires acres of land covered by special reflectors to divert the sun's ray to a central receiver, acting as a heat source.

Shown in Figure I.7.5 is the schematic of a thermal system for space heating using solar energy. Water is circulated in a closed flow loop. The heat source for this loop is the solar collector, heating water through the tube wall, which carries the circulating water. The heat sink is a water storage tank, which is also heated by an auxiliary heat source in cloudy weather and at night. The heat sink for the solar loop acts as a heat source for the space being heated, as the tank water is circulated in a heating coil over which the colder air flows.

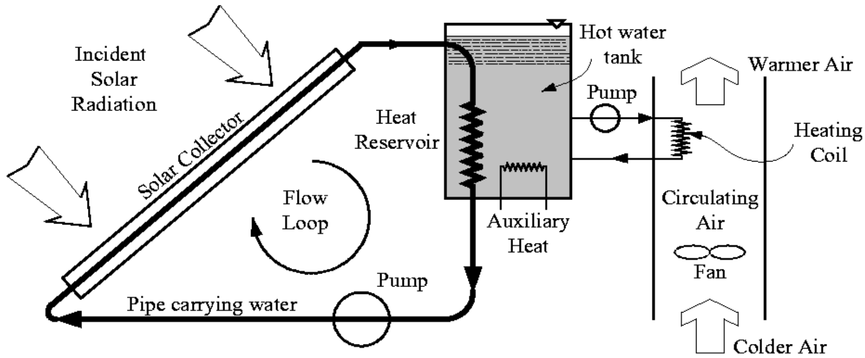


Figure I.7.5. Schematic of space heating by solar energy

7.3. Wind Turbines

Wind turbines convert wind kinetic energy into electricity. The principle of wind turbines is further discussed in Chapter VIc. Among the various types of wind turbines, the most popular is the 3-blade horizontal shaft turbine installed on a tower. The power produced by such turbines is in the range of 0.5 to 1.5 MW. Due to the low density of air, wind turbines must sweep a wide area to produce sufficient torque. One of North America's largest wind turbines produces 1.8 MW of electricity at 29 rpm. This turbine uses 39 m (128 ft) long blades installed on a 78 m (256 ft) high tower. Examples of three-blade horizontal-shaft wind turbines are shown in Figure I.7.6. Other types of such turbines include the vertical axis wind turbine. This machine resembles a giant eggbeater and was patented by George Darrieus in 1931. The advantage of the Darrieus turbine is that there is no need for a yaw mechanism to direct the blades towards the wind and the gearbox is closer to the ground hence, providing easier accessibility.

Figure I.7.6. Horizontal shaft wind turbine

7.4. Tidal Power

Power plants for harnessing tidal power are similar to hydroelectric plants, but are in the sea instead of in a river beds. The motive power comes from the fact that the moon's gravitational effect results in daily high and low tides. The daily surge of water passes through hydroturbines. The first tidal power plant, generating over 300 MWe, was built on the Rance River in France to harness the tidal power of the English channel (Marion). From low to high tide, water rises as much as 44 ft (13.4 m). The plant operates by opening the gates as tide rises to let the channel water enter the Rance River Dam. The gates are then closed at high tide. The trapped water is allowed to flow back to the English Channel at low tide through as many as 24 hydroelectric turbines each producing about 13 MWe. The total energy from tidal power worldwide is estimated at about 2 GWe

7.5. Geothermal Power

The earth's core, due to the formation of the solar system some 4.5 billion years ago, is extremely hot. Indeed at a depth of 40 km, temperature reaches as high as 1000 C. Earth's cross section is shown in Figure I.7.7(a). It is estimated that 7E11 m^3 of superheated water (as defined in Chapter IIa) at 200 C exists beneath the earth's surface (Marion).

Geothermal energy relies on this heat source for power production. In the early part of the 20^{th} century, the potential of geothermal energy for power was recognized. Larderello, the first geothermal power plant was developed in Italy's Tuscany in 1904. The Larderello plant now produces about 400 MWe. Several other countries such as Bolivia, Iceland, Japan, New Zealand, and the U.S. use geothermal energy for power production. In Reykjavik, Iceland, most houses are heated with pipes carrying hot volcanic water. In the United States, potential sites for geothermal energy are found mostly in the Western states such as California, Nevada, and Oregon. Figure I.7.7(b) shows that in 3 decades, power production from geothermal energy in the U.S. has increased by a factor of about 30. It is estimated that by 2010, power production from geothermal sources in the U.S. will reach 5–10 GWe. Unlike solar and wind, geothermal energy has a very high degree of availability hence; it is used as base load for power production. Indeed, the average availability for such plants exceeds 95% compared with about 70% for coal and 90% for nuclear plants. The negative aspects include a) unlike solar and wind, geothermal energy is not a 100% renewable source, as long-term use of such sites would result in steam production at lower pressures or eventual depletion of the source, b) production of such gases as hydrogen sulfide (H_2S), carbon dioxide (CO_2), and nitrogen oxide (NO_x), albeit these byproduct gases are produced in a much smaller scale compared to coal power plants, and c) the removal of underground steam and water can potentially cause the surface to subside. Despite these shortcomings, geothermal energy is indeed a very useful and clean source of energy, and with improving economical aspects it is expected to meet an increasing share of the world's energy needs.

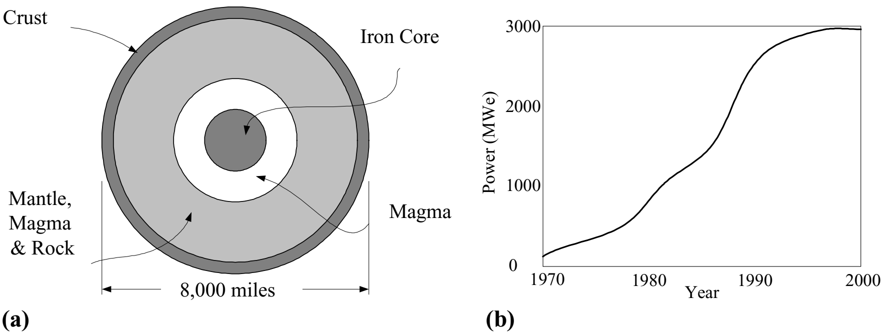


Figure I.7.7. Depiction of: (a) Earth's cross-section; (b) growth of geothermal power in the U.S.

8. Comparison of Various Energy Sources

In Table I.8.1, we have divided the various sources of energy into three major categories as follows.

Carbon-based fuels. While this type of fuel has been the major source of energy for the past two centuries, it is coming under increasing scrutiny. This is because byproducts of carbon-based fuels include CO_2 as well as other gases, referred to as the *greenhouse gases*. Greenhouse gases in the upper atmosphere trap the sun's radiation and increase the retention of thermal energy, which otherwise would have been reflected back into space. Hence, these gases result in an increase in the earth's temperature. This phenomenon, known as the *greenhouse effect* is thought to be responsible for *global warming*.

Nuclear fuels. Nuclear-based energy is combustion free and there are therefore no emissions. However the operational safety and the safe disposal of nuclear waste remain a matter of public concern. The nuclear industry has made substantial improvement in operational safety. The new generation of reactors is designed to maximize safety and reliability by enhancing the passive safety features and reducing reliance on pumps, valves, and emergency diesel generators. Regarding nuclear waste disposal, nuclear plants store the spent fuel assemblies on-site in spent fuel pools, which in many plants have reached their maximum capacity. Nuclear plants in the U.S. have then started to store the oldest spent fuel assemblies in dry storage canisters, which are then housed on-site for passive cooling for eventual transfer to the federal repository at Yucca Mountain, Nevada.

Greenpower. The major problem associated with the renewable resources is low power density, defined as power produced per site area (MW/m^2).

Table I.8.1. Comparison of various sources of energy

Source		Advantage	Disadvantage
Carbon Based	Coal	Relatively easy to recover Established technology	Air pollution (mercury, sulfur dioxide, etc.) Contributor to acid rain and global warming Not easy to transport Acid runoff in coal mines
	Oil/ Gas	Easy to transport Established technology	Contributor to global warming Affected by geopolitical factors Expensive for energy generation Crude oil requires refinement for various use
Nuclear Based	Fission	No greenhouse or acid rain effects Compact waste Inexpensive fuel Concentrated base energy generation	Large capital cost due to regulatory requirements Long term storage of radioactive waste Potential for nuclear proliferation
	Fusion	Unlimited fuel source Low radiation level High energy output per unit mass Manageable waste	Technology for sustained fusion in development
Renew-able*	Hydro	Power source is free No greenhouse or acid rain effects	High water flow or head must be available Environmental damage if land is flooded Adverse effect on fish (salmon) population Large capital cost Susceptible to drought
	Solar	Power source is free No greenhouse or acid rain effects	Dependence on daytime clear weather Large land area for small energy generation Mirrors/panel may affect environment
	Wind	Power source is free No greenhouse or acid rain effects	Limited to suitable areas Needs expensive energy storage Noise pollution Adverse effect on birds Windstorms may damage the unit
	Tidal	Power source is free No greenhouse or acid rain effects	Low specific power Limited to suitable areas
	Geo-Therm.	Power source is free No greenhouse or acid rain effects	Associated with some CO_2, NO_x, and H_2S Economically not yet viable Not available/feasible everywhere

* Not shown in this table is the biomass energy source. Biomass includes the organic material, which convert the sunlight energy into chemical energy, which is then converted to heat when burned. Biomass fuels include such materials as wood, straw, ethanol, manure, sugar cane, and other byproducts from a variety of agricultural processes.

As Table I.8.1 shows, much research and development are needed to find an optimum solution to the issue of energy production. This is because on the one hand with an increasing world population and with energy being a major contributor in the advancement of society, one can expect that energy consumption would have only an upward trend. On the other hand, the environmental impacts associated with various sources of energy are testing the tolerance level of our planet. Regarding the greenhouse effect, while, the impact of CO_2 production on the global atmosphere is still a topic of debate and investigation, it is reasonable to conclude that the production of such gases should be limited. This would in turn limit the use of carbon-based fuels. We then face the problem of finding a suitable substitution to make up for the partial loss of power production from carbon-based energy sources. Our choice for this purpose is indeed limited, given the associated disadvantages of other sources of energy. Since fusion technology is seemingly remote, the two long term alternatives at the present time seem to be the fission reactors with enhanced safety features and geothermal power.

8.1. Saving Energy by Enhancing Efficiencies

An important factor in meeting the energy demand is the application of technology in increasing efficiency at the three stages of production, transmission, and consumption. The electricity produced in most central power plants using steam turbines, is about 1/3 of the total energy consumed. The remaining 2/3 is wasted as rejected heat to the environment. The central stations using gas turbines may have efficiencies in excess of 45% mostly due to operation at higher gas temperatures compared with steam temperature. Voltage drop in transmission lines has been a topic of investigation to find materials, which pose less resistance to the flow of electricity. Superconducting materials have such ability but they must presently operate at very low temperatures. Finally, improvement of efficiency in such home appliances as refrigerators, hot water heaters, heat pumps, washers and dryers would help reduce demand for power.

9. Thermofluid Analysis of Systems

Design and operation of any power producing system must satisfy the imposed constraints such as cost, safety, performance, size, and environmental impact. Here we focus only on the thermofluid aspects. In Section 4 we introduced such systems as pump, turbine, reactor vessel, steam generator, condenser, internal combustion engine, nuclear power plant, wind turbine, etc. There are five fundamental equations for the analysis of all such systems. These five fundamental equations in thermofluid analysis are:

- conservation equation of mass,
- conservation equation of energy,
- conservation equation of momentum (also known as linear momentum),

- conservation equation of angular momentum,
- the second law of thermodynamic

These equations are shown in the hub of Figure I.9.1. However, before these equations are applied, we first need to determine what we mean by thermofluid analysis of a system. This in turn requires us to identify the variables that we call *design parameters* of a system.

We can divide the design parameters into several categories. For example, one category includes the system dimensions such as diameter, height, flow area, and volume. Another category deals with the thermodynamic aspects such as pressure, temperature, and density. A third category might include parameters related to hydrodynamics such as power, momentum, torque, force, acceleration, and velocity.

In any system analysis, some of the design parameters are given and we need to find some other parameters of interest. This is what we refer to as thermofluid analysis of a system.

To perform thermofluid analysis of a system, we must first determine the extent of the system. This is accomplished by using techniques known as *control volume* and *control mass* as described in Chapter IIa. Once the extent of the system is defined, we consider the process applied to the system to identify the appropriate set of equations to use.

Having determined the systen, the involved process, and the specified set of input data, we must then ensure that the number of applicable fundamental equations is sufficient to uniquely determine the number of the design parameters, which are unknown. Also not all the five fundamental equations listed above are applicable to the analysis of a system. For example, if there is no rotational motion involved in the analysis, the conservation equation of angular momentum is not applicable. Even when all the five fundamental equations are applicable, still we may run into the problem of having more unknowns than equations. This problem is remedied (i.e., the number of equations are increased to become equal to the number of unknowns) by introducing additional equations known as the *constitutive equations*, shown as spokes in Figure I.9.1. This figure is one way to visualize the interrelation between the fundamental and the constitutive equations.

Application of the constitutive equations depends on the type of analysis. If the analysis involves heat transfer, temperature and the rate of heat transfer are related by a constitutive equation. This constitutive equation, as discussed in Chapter IV, depends on the mode of heat transfer involved in the process. For example, in conduction heat transfer, the related constitutive equation is known as *Fourier's law* of conduction. Similarly, in convection heat transfer, the related constitutive equation is known as *Newton's law of cooling* while, in radiation heat transfer, the related constitutive equation is known as the *Stefan-Boltzmann* law.

The constitutive equations in fluid mechanics, as discussed in Chapter III, are primarily the *Newton's law of viscosity* and the *Stokes hypothesis*. The constitutive equation in mass transfer is the *Fick's law of diffusion*. The set of constitutive equations that is most often used is the *equation of state* relating the thermodynamic variables of a system. These thermodynamic variables are known as properties, as discussed in Chapter IIa.

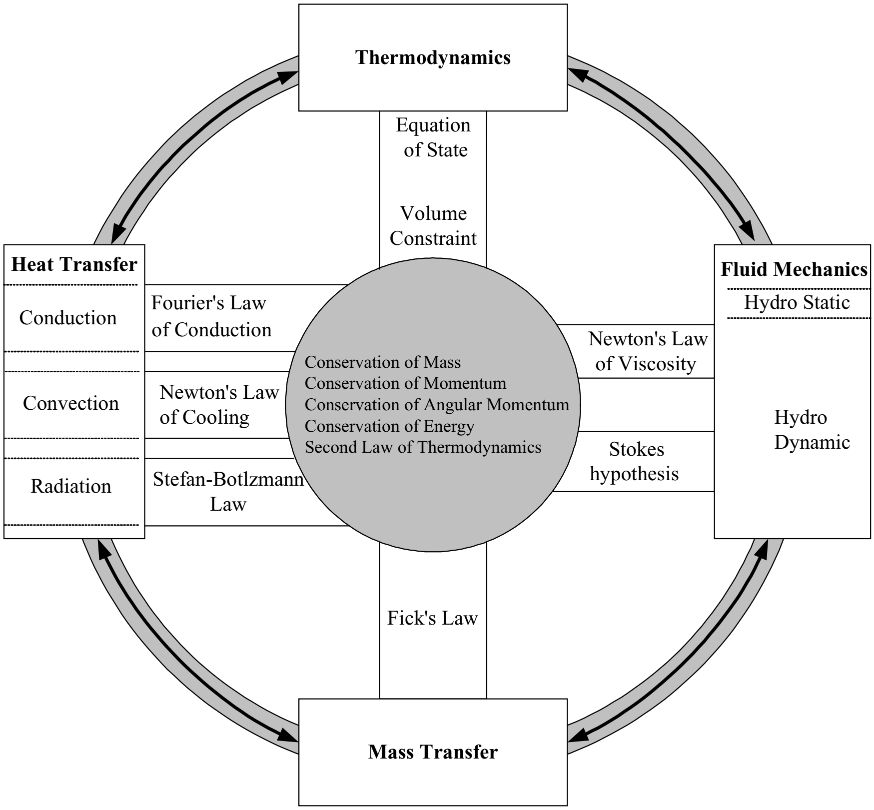


Figure I.9.1. Possible classification of the fundamental *(Hub)* and the constitutive *(Spoke)* equations in thermofluid analysis of systems

QUESTIONS

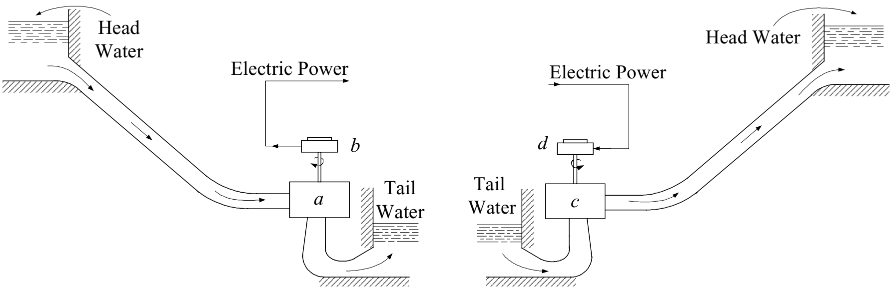
- What types of energy conversion take place in shoveling snow, rowing a canoe, and riding the elevator?
- What is the role of a transformer in the transmission of electricity through the power lines?
- How do you classify condensers, automotive radiators, and cooling towers?
- Is it true to say that the energy associated with fission is primarily due to the released radiation?
- What is the difference between fission and fusion?
- Are fossil power plants using coal for fuel, considered external or internal combustion machines?
- Why does the diameter of a steam turbine rotor increase as steam pressure decreases?
- Why is a nuclear reactor especially well suited for submarines?

- How does a gas turbine operate?
- What are the differences between turbofan, turboprop, and turboshaft?
- What is the key factor in favor of jet engines over internal combustion engines for aviation application?
- Name a disadvantage associated with hydropower plants?
- What are the disadvantages associated with wind power?
- What are the conservation equations? What do they conserve? Is the equation formulating the second law of thermodynamic a conservation equation?
- What is a constitutive equation? Why do we often need to use a constitutive equation?

PROBLEMS

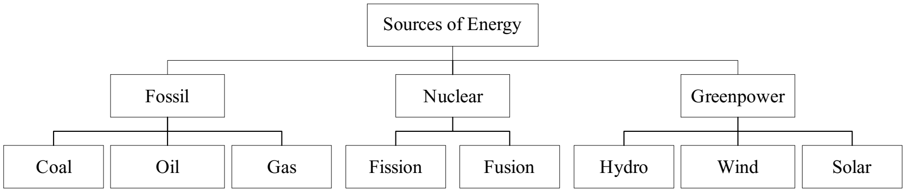
1. Match the upper case with the lower case letters that best describe the conversion of energy:
A. chemical – electrical, B. solar – electrical, C. electrical – thermal, D. nuclear – thermal, E. electrical – mechanical, F. chemical – mechanical, G. kinetic – thermal, H. potential – kinetic.
a. free fall, b. battery, c. plane crash, d. motor, e. solar calculator, f. heater, g. nuclear power plant, h. body muscles.

2. Use your knowledge of power production, power consumption, and energy conversion to find the names of the systems shown as *a* and *b* in the left hand and *c* and *d* in the right hand schematics. [Ans.: *a* is a hydraulic turbine].

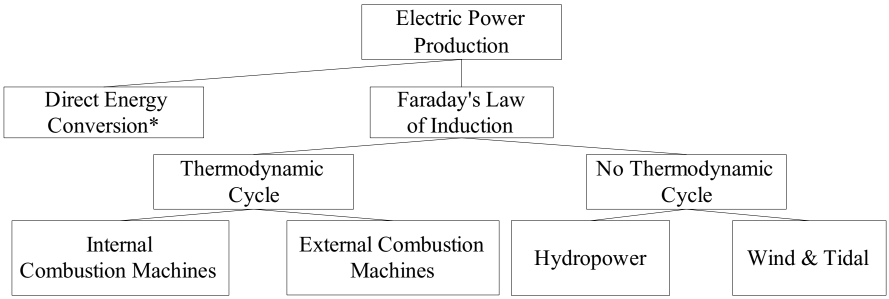


3. Explain the role of energy in water desalination and draw a diagram to represent the operation of such plant. First consider the goal and then try to find the means to accomplish your goal.

4. A simplified diagram of the three major energy sources and examples of each source of energy are shown below. Provide additional examples for sources of energy known as renewable sources or greenpower, and provide a brief description for each of the examples.

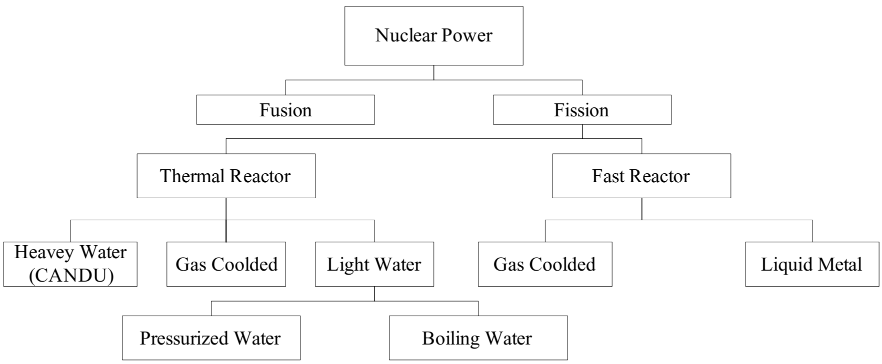


5. Principles of electrical energy production are shown in the simplified diagram. Provide a brief summary for each box comprising the thermodynamic cycle.



* Some direct energy conversion systems such as magnetohydrodynamics use the Faraday law of induction

6. A simplified diagram for nuclear power is shown below. Provide a brief description for each box comprising the light water reactor type.



7. A gas-cooled reactor uses a compressor to circulate helium as the working fluid, through the core of the reactor. The heated gas then enters a gas turbine to produce power. Helium is then cooled in the condenser and pumped back to the reactor. Another gas cooled plant uses a similar cycle but hot gases instead of entering a gas turbine enter a steam generator to boil water in the secondary side. The

cooler gas enters the compressor to be pumped back into the reactor and steam in the secondary side of the steam generator enters a steam turbine. Draw the flow path of the working fluid in each reactor type and describe the advantages and disadvantages of each design.

8. Use schematic diagrams to draw the flow path of both a BWR and a PWR. Explain the flow path in the reactor core for both types of reactors and the flow path in the steam generator of the PWR.

9. During normal operation of a PWR, feedwater enters the secondary side of the steam generator. After being heated by the hotter primary side water, feedwater boils in the tube bundle and dry steam leaves the steam generator and flows towards the turbine through the main steam line. In this condition, water level in the steam generator remains at a fixed level. Is it fair to say that the flow rate of steam out of the steam generator exactly matches the flow rate of the feedwater into the steam generator?

10. Describe the operation of a thermodynamic cycle. List and discuss the role of the various components of a thermodynamic cycle. Describe the operation of a Wankel engine in the framework of a thermodynamic cycle. In this regard, identify the heat source, the heat sink, and the working fluid in an internal combustion engine such as a Wankel rotary engine.